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(54) **ISOTOPIC FIBEROPTICS**

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ABSTRACT:



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(19) (CA) CANADIAN PATENT (12)

(54) Isotopic Fiberoptics

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ABSTRACT

An optical fiber in which chemical non-uniformities leading to optical losses at the core and cladding interface are minimized by selecting materials for the core and the cladding which are chemically substantially identical, at least one element in the core being the isotope of the corresponding element in the cladding and selected to impart a refractive index in the core which exceeds the refractive index in cladding.

ISOTOPIC FIBEROPTICS

This invention relates to the production of an optical fiber in which the number of imperfections between the core and the cladding is substantially reduced so as to minimize attenuation of electromagnetic radiation or light travelling
5 through the fiber and maximize total internal reflection.

Attenuation of light in an optical fiber is partly due to intrinsic factors and also to extrinsic factors. The intrinsic factors are inherent to the component materials comprising a fiber and are generally recognized to include
10 electronic and vibrational absorption, and Rayleigh scattering. Current developments in optical fiber research include the selection of new materials which are selected on the basis of their intrinsic low attenuation properties.

The attenuation of light in an optical fiber may also
15 be ascribed to extrinsic losses resulting from contamination and improper processing. In particular, in silica-based material, an important absorbing species is the hydroxyl radical (OH-) which is formed when hydrogen is present in the fiber material. One approach for reducing the hydroxyl caused attenuation, has
20 been to replace the hydrogen with deuterium so as to shift the vibration mode of the radical impurity to a longer wavelength outside the region of interest.

While the substitution of deuterium for hydrogen in silica-based optical fibers has had the desired effect, and the
25 non-silica-based fiber materials, the so-called second generation fiber materials including halide-containing crystals,



chalcogenide glasses and heavy-metal fluoride glasses are attractive because of their intrinsically low attenuation properties, these approaches do not address physical attenuation factors which necessarily arise at the interface between materials of different chemical composition.

It is the object of this invention to provide an optical fiber in which the opportunity for the attenuation of light at the interface between the cladding and core materials is substantially minimized.

In accordance with this invention, there is provided an optical fiber comprising a core and a cladding in which the core material and the cladding material include at least one common constituent element, the common element in the core being an isotope of the element in the cladding.

Preferably, the core material and cladding material will have the same chemical composition, so that the interface between the core and cladding will be chemically coherent. The material composing the core and cladding are selected so that at least one element in the core material is an isotope of the element in the cladding material and the resulting refractive index in the core exceeds the refractive index in the cladding.

The invention has a theoretical basis which is described below and supplemented by experimental results with reference to the accompanying drawings in which:

Fig. 1 is a schematic representation of the apparatus used for plasma enhanced chemical vapour deposition (PCVD) of isotopic layers according to the invention;

Fig. 2 is a graphical representation of the optical bandgap (ev) on the ordinate axis and layer thickness (μm) on the abscissa for specimens of deuterated and hydrogenated amorphous silicon produced by PCVD with the apparatus of Fig. 1; and

Fig. 3 is a graphical representation of the ratio of the refractive indices minus 1 ($n-1$) on the ordinate axis and the thickness of the hydrated associated amorphous silicon layer on the abscissa for the specimens of Fig. 2.

The expected variations in lattice constant d for isotopically different materials, for typical transparent crystalline solids, may be represented as follows:

$$\frac{\Delta d}{d} \approx 10^{-3} \text{ to } 10^{-4}$$

in accordance with Matthew, J.A.D., 1968. Journal of Physics C, vol. 1, p. 1768.

Based on the first order approximation by the Clausius-Mosotti relationship for refractive index (Blakemore, J.S., 1985. "Solid State Physics", Cambridge University Press), the relation between lattice constant d and refractive index n may be represented as follows:

$$\frac{\Delta n}{n} \approx 3c \frac{\Delta d}{d}$$

where c is a dimensionless adjustment factor of the order of unity.

It follows that a minimum expected ratio of the refractive indices at a typical isotopic interface will range between 3×10^{-3} and 3×10^{-4} or $= n_1/n_2 = 1.003 - 1.0003$.

- 5 from the Snell law of light refraction ($\sin \theta_2 / \sin \theta_1 = n_1/n_2$), applicable to small angles, the following expression for the ray bending angle ϕ at which light travels through a refractive boundary may be deduced:

10
$$\phi = \theta - \arcsin (n_1/n_2 \sin \theta)$$

- where θ is the angle between the falling ray and normal to the interface. For a sliding ray in which $\theta \approx 90^\circ$, the control case for light confinement in fibers, one obtains a ray bending angle ϕ of 1.5 to 4.5 degrees, sufficient for confining light.

- 15 The following experiments were conducted to determine the ratio of the refractive indices n in isotopically different materials. The materials under investigation were hydrogenated amorphous silicon and deuterated amorphous silicon. Sandwiches of varying thickness were produced, with hydrogenated layers deposited on a silicon substrate and deuterated layers deposited over the hydrogenated layers and vice versa.

- 20 Deposition was effected by plasma enhanced chemical vapour deposition (PCVD) in a reaction chamber schematically illustrated in Fig. 1 and generally indicated by the numeral 20. The chamber made of Pyrex (TM), is generally cylindrical in shape and has a length of 65 cms with an internal diameter of 5.5 cms.

The chamber 20 has a gas inlet port 22 at one end and a gas outlet port 24 at the other end which, in use, is operatively connected to a pump (not shown). An anode 26 and a cathode 28 are provided at opposite ends of the chamber 20 and spaced 43 cms from each other. The anode 26 and cathode 28 are electrically connected to apply a high voltage discharge of 500 - 3000V across the chamber and create a chemically reactive plasma in the chamber for enhancing deposition. A plurality of electrostatic probes 32 for monitoring plasma parameters such as electron temperature and plasma density are spaced along the length of the chamber 20 at 70 cm intervals between the anode 26 and the cathode 28.

Silicon substrates, which oxidize very easily, were carefully prepared prior to introduction into the chamber where they were supported on a glass boat 30 placed inside the chamber 20 at the cathode end. The substrates, measuring 1.3 x 1.3 cms, were immersed in a trichloroethylene solution where they were cleaned ultrasonically for five minutes. The trichloroethylene solution was subsequently heated to boiling and the substrates rinsed in distilled water.

The substrates were then introduced into a sulphuric acid and hydrogen peroxide solution (1:1) heated to 80°C for a period of ten minutes. The substrates were then washed with water and placed in a solution of hydrofluoric acid and water (1:5) for five minutes to remove any silicon oxide and washed again.

After placing the substrates into the chamber 20 on the glass boat 30, the chamber was evacuated to a pressure of 10^{-3}

Torr to minimize contamination and pre-heated to a temperature of 120°C for twelve hours so as to remove any remaining water from the substrates.

5 Th chamber 20 was then purged with argon gas and fed a gaseous mixture comprising 95% argon, 2.5% silane (SiH_4) and 2.5% deuterium or 97% argon and 3% silane according to whether the first deposited layer was to be deuterated amorphous silicon or hydrogenated amorphous silicon, respectively.

10 Assuming the former, a direct current power supply of 0.6 KW was applied to establish a discharge current between the anode 26 and the cathode 28 of 10 - 100 mA for a selected period of time sufficient to deposit a predetermined thickness of deuterated amorphous silicon on the silicon substrates.

15 With the power off, the chamber 20 was purged with argon gas and subsequently fed with the 97% argon and 3% silane (SiH_4) gaseous mixture and the power was reactivated to produce a discharge current of 10 - 100 mA and create an argon silane gas plasma between the anode 26 and the cathode 28. The power was sustained until the desired thickness of hydrogenated amorphous silicon was deposited on the inner layer of deuterated amorphous silicon.

25 The procedure was reversed, first feeding the 97% argon, 3% silane (SiH_4) gaseous mixture and subsequently feeding the 95% argon, 2.5% silane (SiH_4) and 2.5% deuterium gaseous mixture to coat silicon substrates with a first inner layer of hydrogenated amorphous silicon and a second outer layer of deuterated amorphous silicon.

Optical bandgap values (E_g) for the deuterated amorphous silicon layers and hydrogenated amorphous silicon layers were measured using standard optical techniques and the results are graphically illustrated in Fig. 2 where the optical bandgap lies on the ordinate axis and the thickness of the respective amorphous silicon layer lies on the abscissa.

At comparable thicknesses of one micrometer, the bandgap values for the deuterated amorphous silicon and hydrogenated amorphous silicon differ significantly, being 2.00 eV and 1.75 eV respectively.

Bandgap values are related to the refractive index in accordance with the Moss relationship (Pankove, J.I., 1971. "Optical Processes in Semiconductors", Dover Publications, N.Y., p. 89.) as follows:

$$E_g n^4 \approx \text{constant}$$

Substituting the experimentally determined values of the band-gap E_g for deuterated amorphous silicon (a - Si : D/H) and hydrogenated amorphous silicon (a - Si:H) at a thickness of 1 micrometer, the ratio of their respective refractive indices is calculated as follows:

$$n = n_1/n_2 = [E_{g2}/E_{g1}]^{1/4} = [2.00/1.75]^{1/4} = 1.034$$

improving on the theoretically expected ratio by one order of magnitude.

It will be understood by those skilled in the art that an acceptable range of ratios of the refractive indices for the core to the cladding is 1.001 - 1.01 and that the above ratio

represents a 3% difference in the refractive indices of the core and cladding thereby providing a light confinement angle of several degrees.

5 In Fig. 3, solid curves were plotted for specimens in which the inner layer is deuterated and the outer layer is hydrogenated. Dashed curves were plotted for specimens in which the inner layer is hydrogenated and the outer layer is deuterated. Each curve joins points having a common deuterated amorphous silicon layer thickness.

10 For the specimens in which the outer layer is hydrogenated, it will be seen that the ratio of the refractive indices of the deuterated layer to the hydrogenated amorphous silicon layer increases as the thickness of the hydrogenated layer increases to reach a maximum peak and decreases for
15 further increases in the thickness of the hydrogenated layer.

For specimens in which the outer layer is deuterated, the ratio of the refractive indices increases for increases in the thickness of the hydrogenated layer.

It will thus be appreciated that a variation of the
20 ratio of the thicknesses of the isotopic layers, and the order of the hydrogenated and deuterated layers, are two parameters whereby one can control the refractive index change required for a particular application.

It will be understood that several variations may be
25 made to the above described procedure for producing isotopic layers on a suitable substrate. It will be apparent to those skilled in the art that conventional methods of chemical vapour deposition (CVD) or of plasma enhanced chemical vapour

deposition (PCVD) may be easily adapted to produce an optical fiber preform wherein the material of the core and the cladding are selected so that their compositions are substantially identical and at least one element in the core is an isotope of the corresponding element in the cladding.

Such a method could, for example, use a tubular silicon substrate adapted to receive a first gaseous mixture of, for example, argon and silane to coat the interior of the silicon tube, and subsequently a second gaseous mixture of argon, silane and deuterium to coat the previously deposited layer of hydrogenated amorphous silicon ($a - Si:H$) with a layer of deuterated amorphous silicon ($a - Si:D/H$). The resultant cylinder would then be heated in conventional fashion to consolidate the core of deuterated amorphous silicon and collapse the hydrogenated amorphous silicon and silicon around it into a solid preform for drawing into a fiber in conventional manner.

A similar procedure could also be adopted to make a preform in which the core is hydrogenated and the cladding is deuterated by making suitable adjustments to the relative thicknesses of the core and the cladding.

It will of course be understood that several variations may be made to the above described method of fabricating a preform and will include substituting the noble gas helium for argon as is well known in the art and that various materials may be selected, within the scope of this invention, to produce the core and cladding.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. An optical fiber comprising a core and a cladding, the core material and the cladding material including at least one common constituent element, said element in the core material being an isotope of the element in the cladding material and selected to impart a refractive index in the core which exceeds the refractive index in the cladding.

2. An optical fiber according to claim 1 in which the core material and cladding material are composed of a single compound whereof at least one element in the core material is an isotope of the corresponding element in the cladding material.

3. An optical fiber according to Claim 1 in which the core material is composed of deuterated amorphous silicon and the cladding material is composed of hydrogenated amorphous silicon.

4. An optical fiber according to Claim 1 in which the core material is composed of hydrogenated amorphous silicon and the cladding material is composed of deuterated amorphous silicon.

5. A method of fabricating an optical fiber preform by plasma enhanced chemical vapour deposition (PCVD), the method comprising:

supplying a first gaseous mixture of an inert carrier gas and silane (SiH_4) to a heated evacuated deposition chamber;

applying an electrical current inside the chamber to create a chemically reactive plasma in said first gaseous mixture and effect deposition of a hydrogenated amorphous silicon (a-Si:H) cladding on the interior of a tubular silicon substrate provided in the chamber;

supplying a second gaseous mixture of said inert gas, silane (SiH_4) and deuterium (D_2) to said chamber;

applying an electrical current inside the chamber to create a chemically reactive plasma in said second gaseous mixture and effect deposition of a deuterated amorphous silicon (a-Si:D/H) core inside the hydrogenated amorphous silicon cladding; and

applying heat to consolidate the core and to consolidate the cladding and substrate about the core.

6. A method of fabricating an optical fiber preform by plasma enhanced chemical vapour deposition (PCVD), the method comprising:

supplying a first gaseous mixture of an inert carrier gas, silane (SiH_4) and deuterium (D_2) to a heated evacuated deposition chamber;

applying an electrical current inside the chamber to create a chemically reactive plasma in said first gaseous mixture and effect deposition of a deuterated amorphous silicon (a-Si:H/D) cladding on the interior of a tubular silicon substrate provided in the chamber;

supplying a second gaseous mixture of said inert gas and silane (SiH_4) to said chamber;

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applying an electrical current inside the chamber to create a chemically reactive plasma in said second gaseous mixture and effect deposition of a hydrogenated amorphous silicon (a-Si:H) core inside the deuterated amorphous silicon cladding; and

applying heat to consolidate the core and to consolidate the cladding and substrate about the core.



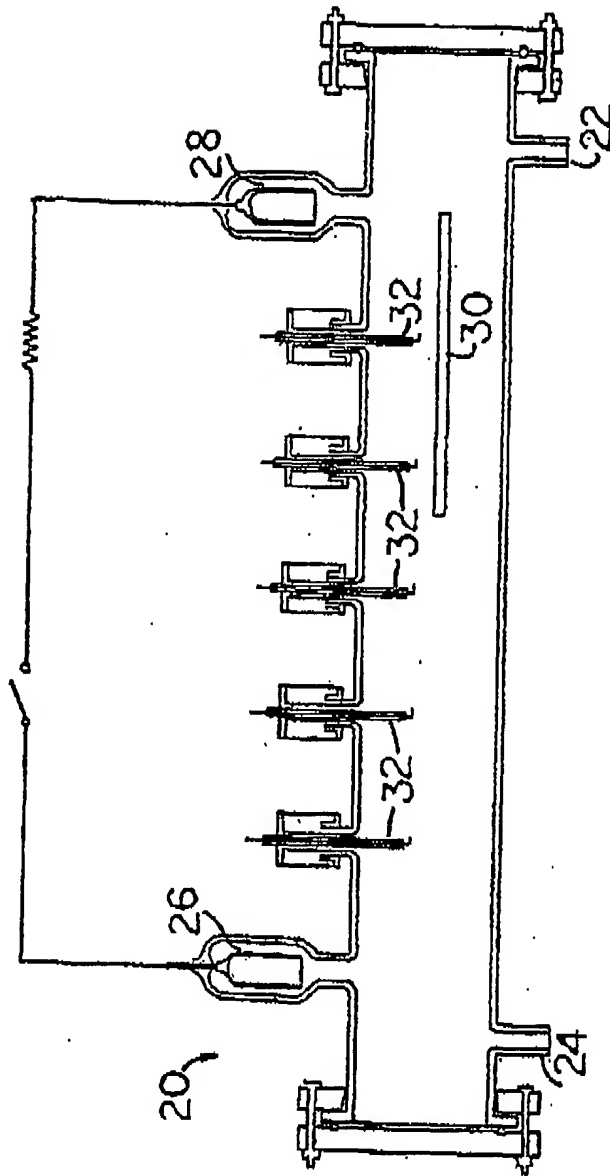


FIG 1

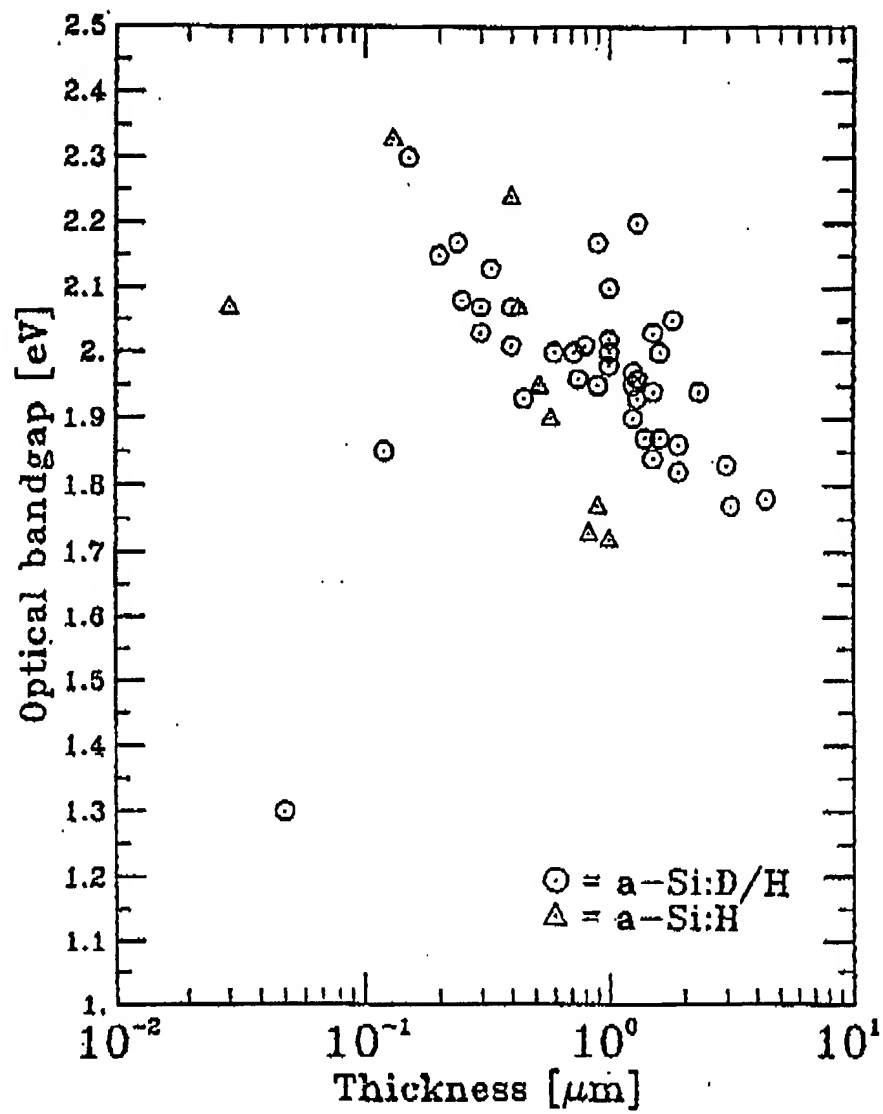


FIG 2

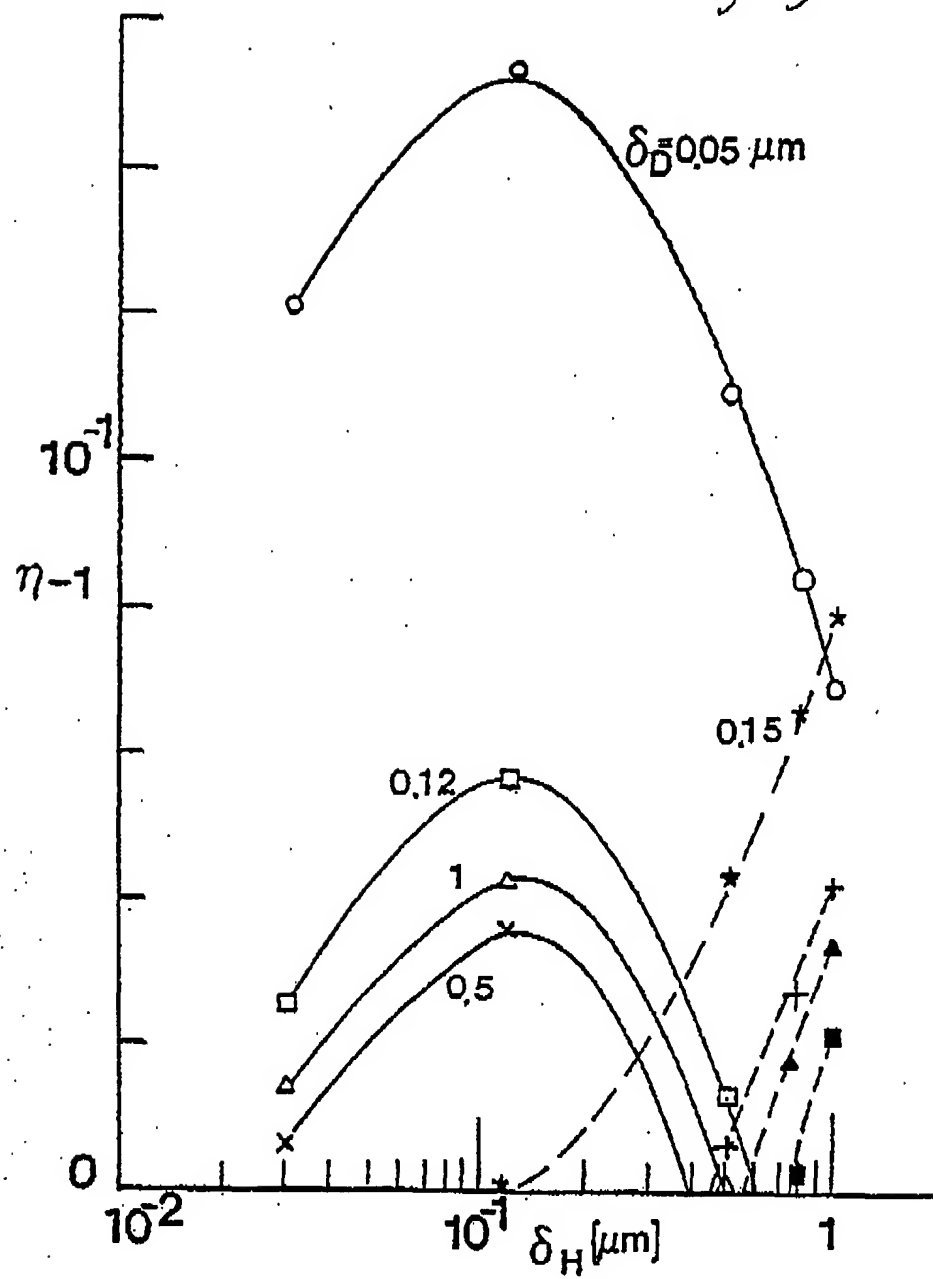


FIG 3